

# HEAT CYCLE TEST FOR STATIC CHARACTERISTICS OF DUAL GATE TYPE MOSFET FOR USE IN NMR APPARATUS

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The static drain current-gate voltage characteristics have been examined at 300, 77 and 4.2 K of the commercial dual gate type MOSFETs (3SK35-5J), which are to be used as active elements in a low temperature marginal type NMR apparatus including the oscillator, amplifier and detector circuits. The effect of several heat cycle tests (by repeated cooling and warming between 300 and 77 K) on the static characteristics at 300 and 77 K are investigated to find out the most probable bias voltages for each circuit;  $V_{G1S} = -1 \sim -0.5$  V for both the oscillator and detector circuits and 1 V for a class A amplifier,  $V_{G2S} = 1$  V for all circuits, and +B supply voltage (or  $V_{DS}$ ) = 3  $\sim$  4 V. Also the bias voltage of the FET for use in the detector is measured as a function of the bias resistance.

## 1. INTRODUCTION

In recent years, solid state devices such as germanium junction (JFET) and silicon metal-oxide-semiconductor (MOSFET) field effect transistors have received a good deal of attention to the useful active circuit elements working at liquid helium temperature.<sup>1)</sup> Generally, these transistors are classified as to material (Si or Ge), doping (p- or n-channel), type of gate (junction or metal-oxide), number of gates (single or dual), operation mode (depletion or enhancement of the carrier density in the channel by the gate voltage), and intended use (amplifier or switch). In principle, the current in the conducting channel is controlled by the electric field established by the gate voltage and the behavior of the device should be substantially independent of temperature, as long as the conductivity of the channel material holds up. There have been numerous reports on the low temperature operation of various FETs, of the junction type (JFET)<sup>2)</sup> and MOSFET type<sup>3,4)</sup>.

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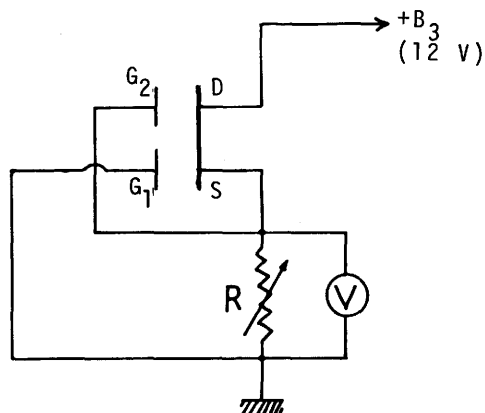
Meanwhile, we have been developing and attempting various improvements for a low temperature NMR apparatus using commercial MOSFETs. In the early work, a single MOSFET (dual gate and n-channel type Toshiba 3SK35) was used as an active element in the LC (tank) circuit of a marginal oscillator; with this simple apparatus we obtained the NMR signals of  $\text{Al}^{27}$  nuclei in ruby crystal at 77 and 4.2 K.<sup>5-7)</sup> Then the marginal oscillator was improved by incorporating an additional MOSFET (as a buffer amplifier) next to the oscillator in order to stabilize the low temperature operation.<sup>8-10)</sup> At the same time we studied the effect of a magnetic field on the static characteristics of the FET elements; as a result, these were found to work well even at low temperatures, but the field direction relative to the plane of the FET was of importance. Furthermore, a diode detector (kept at room temperature) used previously was replaced by the same FET, so that the detector circuit also could be operated at low temperatures.<sup>11)</sup>

In principle, the gain and nonlinearity of these active elements will be increased at low temperature and the resulting overall sensitivity of the NMR apparatus will be raised. However, we have often encountered with the difficulties of reproducibility of actual operations. In the present work, we have investigated the heat cycle test for the static characteristics of the commercial FETs between room temperature and liquid nitrogen temperature and attempted to find out the best conditions for bias voltage of each circuit such as oscillator, amplifier, and detector. Other circuit elements such as resistors and capacitors have already been examined.<sup>11)</sup>

## 2. EXPERIMENTAL METHOD

In the present experiment, we confine ourselves to the static characteristics of the MOSFETs, although are important the dynamic characteristics, as well as the overall operations of the NMR apparatus, over a wide range of frequencies. Figure 1 shows the test circuit

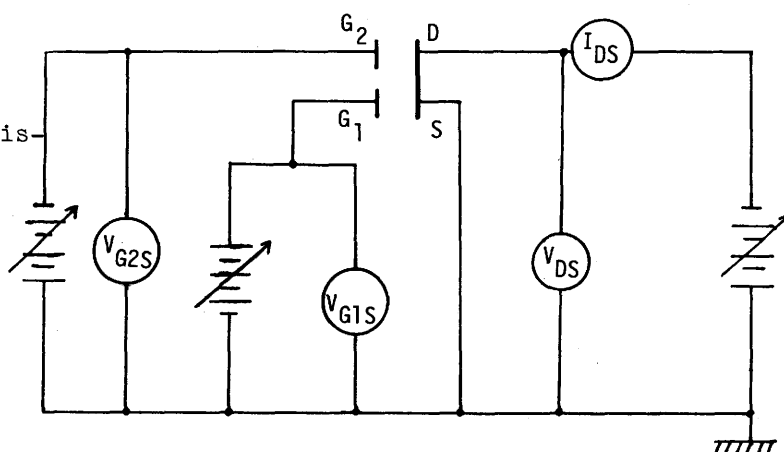
Fig. 1. A test circuit for the dual gate type MOSFET to find out the suitable bias voltage  $V$ ;  $R$  the bias resistance,  $D$  the drain,  $S$  the source,  $G_1$  the gate 1, and  $G_2$  the gate 2 of the FET.



for the dual gate type MOSFET (Toshiba 3SK35-5J) used in the detector circuit. When a bias resistance  $R$  is varied, the drain-source current  $I_{DS}$  is changed, resulting in the change of the bias voltage  $V$ . At the normal working condition of a MOSFET, the voltage  $V$  increases with increasing the resistance  $R$  until a cut-off voltage where  $V$  does not increase any more with  $R$ . This test circuit is used to find out a suitable bias resistance.

The static characteristics were examined by a test circuit shown in Fig. 2. The gate 1-source voltage  $V_{G1S}$  was measured as a function of drain-source current  $I_{DS}$ , while the gate 2-source voltage  $V_{G2S}$  and drain-source voltage  $V_{DS}$  were fixed at constant values as parameters.

Fig. 2. A test circuit for the static characteristics of the MOSFET.



In these test circuits only the MOSFET was immersed in liquid  $N_2$  bath, while the others including meters and leads were kept at room temperature. The heat cycle test was carried out by cooling the FET rapidly down to 77 K and warming it slowly up to room temperature----one heat cycle test.

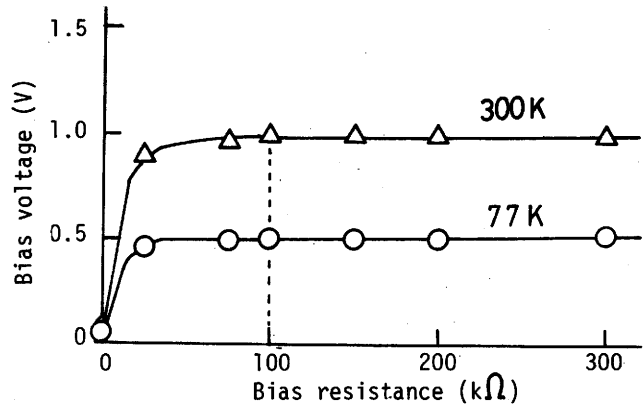
### 3. RESULTS AND DISCUSSION

In Fig. 3 is shown the bias voltage  $V$  against the bias resistance  $R$  at 77 and 300 K for a MOSFET (3SK35-5J), measured by the test circuit of Fig. 1. It can be seen that with increasing  $R$  the voltage tends to level off to a constant voltage (a cut-off voltage) for a higher resistance above the dashed line; the cut-off voltage at 300 K reduces to about half at 77 K. Some of the commercial FETs did not show such a saturation characteristic after or even before the heat cycle test.

Typical  $I_{DS}$ - $V_{G1S}$  characteristics of the MOSFET at three fixed temperatures are shown in Fig. 4 for the different gate 2-source voltages  $V_{G2S}$  (0 and 2 V), where the drain-source voltage  $V_{DS}$  is fixed

constant; (A)  $V_{DS}=1$  V, (B)  $V_{DS}=3$  V and (C)  $V_{DS}=5$  V. Though not shown

Fig. 3. The bias characteristics at two temperatures for a MOSFET (3SK35-5J), measured by the test circuit shown in Fig. 1. The bias voltage saturates completely for  $R$  more than the dashed line.



in Fig. 4, we found at liquid He temperature that for  $V_{DS}>5$  V the drain current  $I_{DS}$  of the FET rised sharply and exceeded its break-down current ( $\sim 30$  mA). The drain current  $I_{DS}$  at 4.2 K for  $V_{G2S}=0$  in Fig. 4(A) was negligibly small to be measured.

Characteristic features of the observed  $I_{DS}-V_{G1S}$  curves are to be noted as follows: (i) For  $V_{G2S}=0$ ,  $I_{DS}$  is decreased as the temperature is lowered. (ii) For  $V_{G2S}=2$  V, it tends to increase with decreasing temperature, but the behavior is complicated depending on the value of  $V_{DS}$ . (iii)  $I_{DS}$  is likely to saturate at a lower bias voltage  $V_{G1S}$  at 4.2 K than that at 77 K. (iv) The slope of each curve, or the conductance  $dI_{DS}/dV_{G1S}$ , tends to become steep at lower temperatures. (v) The cut-off voltage of  $V_{G1S}$ , at which the drain current begins to increase, varies appreciably with temperature but slightly with  $V_{DS}$ , as summarized in Table I.

Table I. The cut-off voltage  $V_{G1S}$  in volt units at three fixed temperatures for different drain voltages  $V_{DS}$ .

$V_{DS}$ (V)	$V_{G2S}=0$			$V_{G2S}=2$ V		
	300 K	77 K	4.2 K	300 K	77 K	4.2 K
1	-1.12	-0.57	0.70	-1.12	-0.65	0.05
3	-1.12	-0.65	0.20	-1.16	-0.47	-0.08
5	-1.13	-0.65	0.05	-1.16	-0.50	-0.30

Finally, the results of heat cycle test for the FET are illustrated in Figs. 5 (A)~(D). All the  $I_{DS}-V_{G1S}$  characteristics were taken at 300 K (A and B) and 77 K (C and D), before and after heat cycles (5 and 10 times), under a constant drain voltage  $V_{DS}=12$  V higher than those

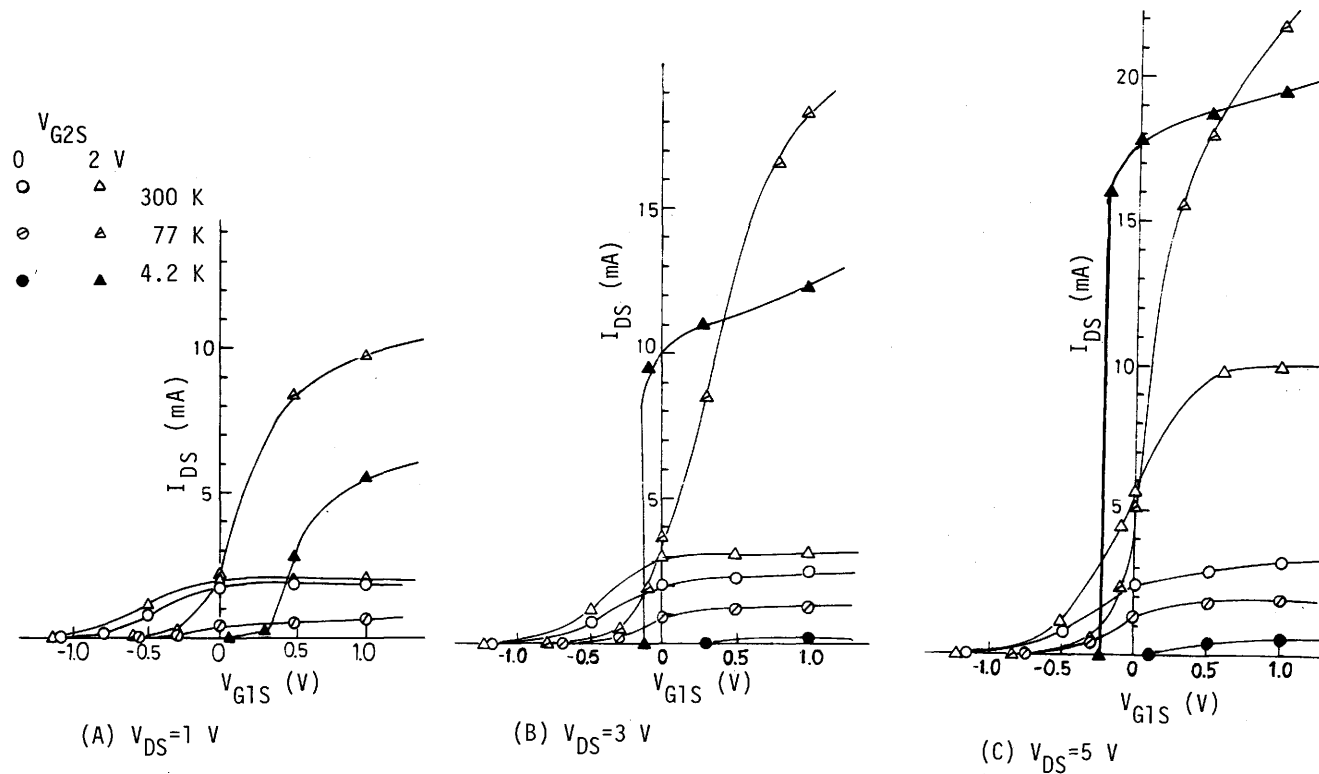


Fig. 4. Typical  $I_{DS}$ - $V_{G1S}$  characteristics of a MOSFET (3SK35-5J) at three fixed temperatures (300, 77 and 4.2 K) for different gate 2 voltages  $V_{G2S}$  (0 and 2 V); (A) the drain-source voltage  $V_{DS}=1$  V, (B)  $V_{DS}=3$  V and (C)  $V_{DS}=5$  V.

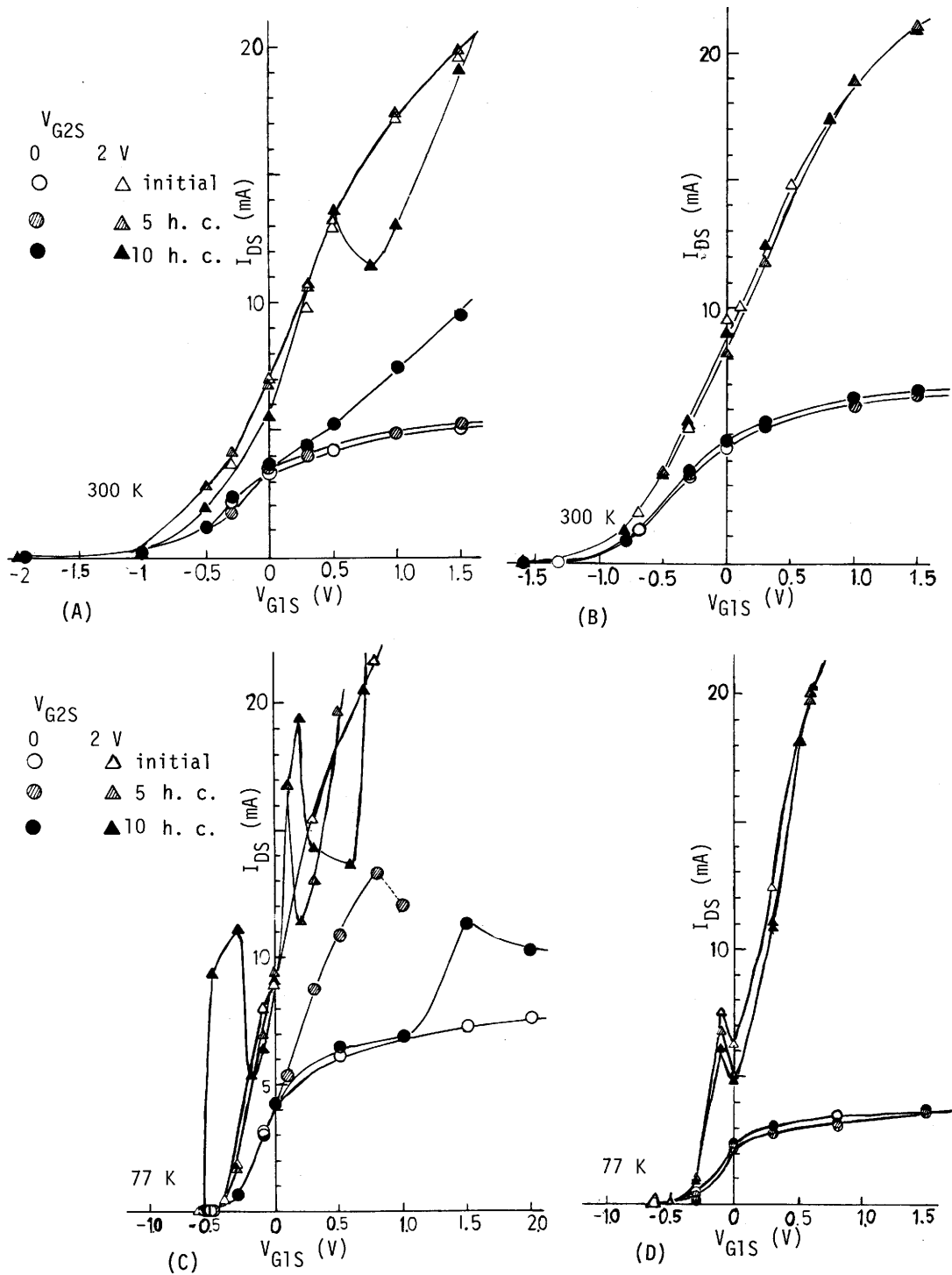


Fig. 5. The effect of heat cycle test (5 and 10 times) on the  $I_{DS}$ - $V_{G1S}$  characteristics of the MOSFET (3SK35-5J) at 300 K (A and B) and 77 K (C and D), measured at a constant drain-source voltage  $V_{DS} = 12$  V, for a bad FET (A and C) and a good FET (B and D).

of Fig. 4. Here the heat cycle (h.c.) means the repeated cooling and warming of FETs between 300 K and 77 K, as described previously. We have particularly paid attention to the reproducibility of  $I_{DS}-V_{G1S}$  characteristics; some of the commercial FETs are good and some are poor. Figures (A) and (C) are the examples of a bad FET, while (B) and (D) are those of a good one. It is apparent that the good FET shows the reproducible characteristics even after the thermal treatment, whereas the I-V curves of the bad FET is rather irregular, in particular at 77 K (Fig. 5 C). Furthermore, it is noted that the cut-off voltage at 300 K of the bad FET shifts considerably towards a negative side (Fig. 5 A), but it remains nearly constant ( $\sim 0.5$  V) at 77 K, regardless of the heat cycle test. Such degradation of static characteristics of the FET elements may be attributed to a structural damage due to thermal contraction and expansion in the metal-oxide layer or in the bulk silicon base.

#### 4. SUMMARY

In order to improve the low temperature NMR apparatus using solid state devices of commercial dual gate type MOSFETs as active elements, we have here examined some of their static characteristics at 300 and 77 K, before and after a repeated thermal treatment. Although each static characteristic may practically differ by sample-to-sample, the general trends for the results of heat cycle tests can be summarized as follows:

- 1) A good FET shows a reproducible characteristic, in which the drain-source current  $I_{DS}$  is a smooth function of the gate voltage. The cut-off voltage of the FET shifts from a negative to a positive side as the temperature is decreased. Under several heat cycles, however, the cut-off voltage does not change. The  $I_{DS}-V_{G1S}$  characteristic at a low voltage of  $V_{DS}$  is particularly reproducible.
- 2) On the contrary, a bad FET shows a degradation of the static characteristics, in particular, at low temperatures.

When we apply the commercial MOSFETs (3SK35-5J) to our NMR apparatus including the oscillator, amplifier, and detector circuits, the following bias conditions are to be recommended on the basis of the above data.

In Table I are given some of the probable bias values for each circuit.

- i) For use in the oscillator circuit as an active element, the bias voltage of  $V_{G1S}$  is to be set in the range  $-1 \sim -0.5$  V, corresponding to the cut-off voltage in the  $I_{DS}-V_{G1S}$  curve. In the NMR marginal technique, a maximum sensitivity of the signals can be attained by adjusting the drain-source voltage at a critical counterbalance between the stop and

Table II. Recommended bias voltages of the dual gate type MOSFET (3SK35-5J) for use in a low temperature NMR apparatus.

Circuit	$V_{G1S}$ (V)	$V_{G2S}$ (V)	$V_{DS}$ (V)
Oscillator	-1 ~ -0.5	1	Variable
Amplifier	0	1	3 ~ 4
Detector	-1 ~ -0.5	1	3 ~ 4

work of oscillation, as already reported.<sup>5-7)</sup> This critical condition varies with temperature, so that the  $V_{DS}$  value must be adjustable.

ii) In the amplifier circuit, used mostly as a class A type, the  $V_{G1S}$  bias should be adjusted to near the part of good linearity in the  $I_{DS}$ - $V_{G1S}$  characteristic; thus  $V_{G1S} \approx 0$ .

iii) The FET detection is operated around the cut-off voltage, and also in this case  $V_{G1S}$  is in the range -1 ~ -0.5 V.

iv) The  $V_{G2S}$  bias is recommended to be about 1 V, since for  $V_{G2S} > 2$  V the linearity of the  $I_{DS}$ - $V_{G1S}$  characteristic becomes poor, while for  $V_{G2S} \approx 0$  the drain current is vanishingly small at low temperatures.

v) Both in the amplifier and detector circuits, the probable value of the +B supply (or the drain-source voltage  $V_{DS}$ ) should be in the range 3 ~ 4 V. As shown in Fig. 4,  $I_{DS}$  increases steeply with  $V_{G1S}$  for further high  $V_{DS}$  value, especially at 4.2 K.

By taking account of these various factors, we are trying further improvements of our NMR apparatus.

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